EXTRATERRESTRIAL IMPERATIVE

By Dr. Krafft A. Ehricke
Chief Scientific Advisor
North American Rockwell/Space Division

Introduction

"Earth is the only luxury passenger liner in a convoy of freighters loaded with resources. These resources are for us to use after earth has hatched us to the point where we have the intelligence and the means to gain partial independence from our planet — and where the time has come to convert our earth from an all-supplying womb into a home for the long future of the human race, finally born into the greater environment of many worlds." Krafft A. Ehricke, a Space Age pioneer, is Chief Scientific Advisor, Advanced Programs, Space Division, North American Rockwell. This article is based on a talk to the National Space Meeting of the Institute of Navigation, Huntsville, Alabama, in February 1971. It contains excerpts and condensations from a forthcoming book of the same title by the author and E.A. Miller, to be published by Doubleday, Inc.

Once earth was, to man, the center of the universe — for all practical purposes, infinite and indestructible. Man's mind and soul evolved in this infinite world. He has known no other. Then, astronomy reduced earth to a tiny planet, circling an average star somewhere in an unlimited universe. But, totally conditioned to boundless environment, man's social, political and economic behavior continued as if earth were infinite and indestructible.

In the past 100 years, industrialization, world commerce, world wars, the "bomb," technology, population increase and, finally, pollution have progressively turned our planetary "infinity" into an illusion. Avoidance of war, still so recently the cherished panacea for all of man's problems, now proves to be too simplistic a goal. The pollution issue has added another dimension to man's capability of provoking catastrophes on a global scale.

Concurrent advances in planetary exploration drove into public awareness the not-so-new recognition that earth is a singular world in this solar system. After 500 years of bold and vigorous expansion, a reaction has set in. Man seems to be locked into a cosmic reservation that, for all its wealth, threatens to be a scanty Eden for his numbers and aspirations in the future.

The result is a new kind of disillusion, a wave of pessimism that tends to undermine man's confidence in a soaring future — and therewith, in his nature which, some claim, must be altered radically to conform with what is called insurmountable limitations. Confidence in a soaring future — spiritually as well as materially — is the essence of our techno-scientific civilization and Western man's greatest message to mankind. Erosion of this confidence threatens the value system and weakens the drive on which our monumental accomplishments rest, ever since the dawn of the Renaissance. And, nowhere are the roots of the Renaissance spirit more deeply embedded than in history's boldest social achievement, the United States of America.

A science policy that places the protection of our environment over man's overall needs of tomorrow is not realistic, however well-meaning, because preservation of the environment is only a necessary, not a sufficient requirement. It is no more sufficient for the preservation of man than is a pretty cage for the preservation of an animal born free in the wilds of an infinite world.

Space is obviously not a panacea for all of man's problems. Neither is earth, in the long run, because of its sensitive biosphere and its limited resources. We need both. Man has needs that will outgrow his planet in time. This is not an unrealistic notion — to presume that he will not try virtually anything to satisfy these needs, is. These very needs are so powerful that they — not his inability to see what he is doing — have put man and environment on their present collision course.

The notion that man will, in the centuries and millennia ahead, submit to a slowly declining living standard in harmony with a slowly degrading terrestrial environment is, of course, not an impossible one — but it is rather absurd. A healthy mankind is not that docile, stretching, and growing on challenges and impossible dreams; and it makes little difference whether these challenges and dreams are found on earth or beyond. Man's relation to nature has always been dictated by two passions — love and conquest.

Preservation, therefore, has a much deeper meaning in our time than ever before: that is, not only must we preserve our world's environment, we must also preserve the reality of our world's infinite expanse because man's nature is attuned to it as much as his eyes are attuned to the sunlight spectrum. This means that if we were to single out our one overriding generic responsibility to future generations, it is that we should lay the foundations for a world in which man can act as he must or, in any case, as he does. For modern man, with his powers, this is a world which is what earth alone once was to earlier man. It is not merely a world that is a gilded environmental cage where he can only act as he should by the imperatives of a static existence, or else perish. This means we must give man of tomorrow a world that is bigger than a single planet.

Of course, man should strive constantly to apply a higher degree of reasonableness to his affairs in order to improve the quality of life, even within the limits of terrestrial resources. But it is a fact that man finds his powers of intelligence and reason perpetually distorted by instinctive drives and emotional forces. If we expect this to change significantly in the foreseeable future, we are not being realistic — and neither will be our policy and planning.

We have no effective alternative but to plan for a world in which earth and space are indivisible. We still have time to accomplish the transition.

A realistic assessment of the present situation does not support the apocalyptic claim that this planet will be destroyed in the short order of a a few decades. The very awareness of the dangers ahead triggers remedial action. It is still within our control to reduce the worst transgressions, and subsequently proceed to deal with the more subtle dangers as we become progressively more knowledgeable and capable. Remedial and ameliorative measures can be introduced judiciously; the pace of change depends upon the crisis level of the problem.

In this manner, we can assure for ourselves a viable grace period — of the order of a century — during which to accommodate (1) a growing world population, if the growth rate slows down; (2) a growing world consumption rate, if earth resources management is improved by action in space and on the ground; and (3) growing industrial-agricultural productivity, if that productivity is ameliorated by the benign industrial revolution.

The indivisiblity of earth and space will enhance and favor the inviolability of earth more safely in the long run than can planetary confinement of man. Since the beginning of recorded history, it has been a fundamental goal of civilizations to search for civilizing motivations of their cultural activities. Where will this continued search have a greater chance of success — in the shrinking world of earth or in the expanding world of indivisible earth and space?

Recognition of the uniquenes of our planet has become part of conventional wisdom. But, like everything, uniqueness is not all good. Moreover, our planet is not all that unique. Earth shares many common characteristics with other planets, especially the rocky planets and asteroids (Fig. 1). Within the next 100 years, the nonuniqueness of earth will play a growing role in our attempts to preserve this uniqueness without paralyzing our future. This is not man's only environment, merely his only unique environment.

Earth's unique features are its atmosphere, huge hydrosphere, abundant biosphere and, therefrom, vast deposits of fossil energy. These features provide us with the only livable planet around. Their deterioration by pollution precipitates an environmental crisis.

But this uniquenes cuts both ways: it is the basis of our existence. But it is also the principal constraint on man's industries and technology, on which he must rely to sustain his growing numbers. This is because the uncultivated, unprocessed biosphere has long ceased to satisfy man's needs. Nature could sustain only a fraction of today's 3.7 billion people on a very modest living standard, probably not more than a billion. (Only 300 years ago, at the end of the preindustrial era, the world population was about 500 million; thus, 1 billion is probably a generous estimate.) Therefore, 3.7 billion people must produce to barely survive. They must produce much more in order to provide a bearable standard of living. They must produce at a feverish pace to sustain 6, 10 or 15 billion people.

In the last analysis, the question before us is whether we will continue in the long run to insist on endangering the unique environment of earth — our greatest basic resource, if left as much untouched as possible to exploit resources that are not uniquely earth's and to carry out industrial activities that are not tied to earth's unique environment?

The nonuniqueness of earth is as important to our future as is its uniqueness. The fact that we do not have to depend on earth for everything is the key to our future. It makes possible the gradual evolution of a practical division of labor in an indivisible earth-space continuum — a domain of many environments, each serving us to maximum advantage and each assuring the preservation not of the one but of the two great uniquenesses of this solar system, man and earth's biosphere.

To achieve this division of labor, man needs only to engage the most valuable of all the unique resources at his disposal: his intelligence and his determination. Will we use this resource properly and in time?

One might anticipate for the next 100 years an increase in world consumption level by, at least, a factor of 40, whereas, a more likely increase is a factor of 160 and quite possibly more.

The estimated electric power consumption, for 1970, is about 1.7 trillion kW-h for the U.S. and about 6 trillion kW-h on the world level. These figures are twice the 1960 value. At such an annual growth rate (about 7 percent), the world's energy consumption will pass the 100 trillion kilowatt-hour mark by 2010. The thermal heat release is, characteristically, 2.5 kW-h per electric kilowatt-hour. The heat is released into the environment, passed through the biosphere (hydrosphere, atmosphere) and, eventually, is radiated into the infinite heat sink of space. If sufficiently large this heat release becomes a thermal burden on the biosphere.

The projected global thermal burden in the form of waste heat from electric power generation amounts to about 30 trillion thermal kilowatt-hours in 1980 (Fig. 2). This is only about 8 percent of the solar energy absorbed annually by all terrestrial vegetation (3800 trillion kilowatt-hours). At the present 7 percent growth rate, this value would be reached by 2050, thus, doubling the natural heat flux into the biosphere. By the year 2110, the thermal burden would equal the solar energy absorbed annually by the earth's hydrosphere (about 221 600 trillion kilowatt-hours). But these figures are not realistic, since long before most of the basis of our biosphere — the photosynthetic process in the oceans — would have been destroyed and oxygen regeneration of our atmosphere seriously impeded if not halted altogether. At the previously mentioned growth facto_s of 40 to 160 between 1970 and 2070, the thermal burden from electric power generation would, by 2070, reach 16 to 63 percent of the solar energy absorbed annually by terrestrial vegetation. This range is already quite critical, considering that the actual value is likely to be closer to the upper than the lower value, and considering further that actual heat release will cause local concentrations of extremely biocidal thermal pollution. At 16 percent, the heat influx into the biosphere is about 600 trillion kilowatt-hours, enough to raise the temperature from ambient to the boiling point of some 60 percent of all fresh water lakes on earth. Thus, it is a definite possibility that fresh water life is mortally threatened on a continental scale in the highly industrialized regions of earth. Ocean life in the estuaries and other fertile regions can be seriously threatened by the combination of temperature increases and chemical pollution. Pollution watch of continental coastlines, from satellites or space stations, will become increasingly important.

Space Power Plant

Yet, without energy our techno-scientific civilization cannot be preserved. If our techno-scientific civilization collapses, the lives of billions of people cannot be preserved — a death toll equaling or exceeding that of a massive nuclear exchange. Thus, energy is one of the sectors of man-environment interaction in which we will reach the confrontation phase within 100 years from now. New approaches are required.

Three benign methods of electric power generation are available, constituting long-range solutions to man's energy problems: geothermal, nuclear fusion, and space power generation. It is quite possible that a combination of these will provide the most desirable flexibility to meet future practical needs.

The third approach to a long-range energy solution is the generation of power in space. With the advent of beamed power transmission technology it becomes possible to generate power in space for consumption on earth.

Beamed power transmission will be of almost unlimited consequences for space operations and the opening of moon and planets. Power generation in space for power consumption on earth is a significant example of the future division of labor in the indivisible earth-space continuum of human activity (Fig. 3).

Power generation is the conversion process of energy from its primary form (heat or radiation) to energy in its desired form. On earth, the desired energy form is electricity. In space, the desired energy form is radiation, suitable for transmission to the surface. In any case, it is the initial conversion of primary energy that produces the greatest thermal waste and the greatest chemical waste if the power plant operates on coal or oil. Therefore, transplanting this process into space removes the bulk of the environmental burden associated with the generation of electric power.

Power generation in space involves a primary energy source, conversion to electric energy and conversion to beamed energy, beam transmission to a central receiver ground station, reconversion into electric energy and regional distribution to consumers through high-voltage grids. At least 80 percent of the thermal waste produced in the entire process is generated in space and radiated directly into the cosmic energy sink without first passing through the biosphere. The conversion process from beamed to electric energy in ground stations is better than 80 percent. The chemical or nuclear (fission) waste burden is eliminated entirely.

The primary energy source of a space power plant could be solar radiation or nuclear energy. Solar energy at the earth's distance from sun is rather diluted. One square meter (about 10 square feet) receives about 12 200 kW-h annually. To generate 1 trillion kilowatt-hours annually for the terrestrial consumer at 10 percent overall efficiency requires a solar radiation interception area of about 8 billion square feet (200 000 acres or 320 square miles; or a square measuring 56.6 by 56.6 miles). The actually obtainable overall efficiency will lie between 10 and 15 percent, so that the required intercept area for 1 trillion kilowatt-hours will measure between 320 and 214 square miles. (A recent study by Peter Glaser of a 10-million-kilowatt solar electric power generation system arrived at a solar cell area of 25 square miles. This would correspond to an overall conversion efficiency of 11.2 percent.) This or preferably, a modularized version consisting of, say, several smaller primary energy conversion systems is certainly feasible, considering the technology of the next 30 to 50 years.

An alternate way of using solar energy is by means of radiation collectors, an array of mirrors in whose focal region solar radiation is absorbed by heaters and converted to electric power. Depending on the conversion system, the efficiency of this system could exceed that of a solar array, resulting in a smaller collector panel whose size, however, nevertheless measures in square miles.

The concentrated form in which nuclear energy is available offers many advantages in terms of the cost of establishing the station and its maintenance. Breeder reactors could be used, combining the production of valuable isotopes and uranium-235 with the generation of electric power. The radioactive substances would be stored in space and brought to earth safely, in space shuttles, on the basis of need. The most concentrated form of large-scale nuclear-electric power generation — short of fusion generators — would be a combination of gas core reactor (GCR) and magnetohydrodynamic (MHD) converter. The degree of compactness of such a system can be inferred from the fact that a 15 000 kW (earth) solar power generator system (producing 0.13 billion kilowatt-hours) would require an interceptor area of 1000 by 1000 ft, whereas a GCR-MHD system of the same capability would measure less than 20 ft in diameter. The weight of a GCR-MHD system would run between 70 and 80 percent, possibly less, of the solar energy system.

Nuclear energy is far less difficult to handle in the vacuum of space than on earth and, of course, all apprehensions (which are known to extend far beyond the normal environmental misgivings) relative to the large-scale use of nuclear energy in terrestrial power plants are eliminated. Transportation of fissionable material by a Space Shuttle involves negligible hazards, because the Shuttle is designed for safe abort. The use of nuclear reactors in orbit is for all practical purposes perfectly safe, since the need for neutron reflectors and shielding renders the structure virtually impregnable for space debris or for meteoroids of any practical size.

Thus, we have, for space power plants, a choice of two primary power sources — solar and nuclear — and an eventual optimal arrangement might involve an integration of both into an overall system.

The size of the beam transmitter area depends on the practically feasible power density. This density can vary from many kilowatts per square centimeter for laser beams to the order of 0.5 W per square centimeter for microwave beams. For the latter case, transmission of 1 trillion kilowatt-hours annually at constant power level requires a transmitter area of 10 square miles. On earth, the dimensions of the receiver complex are determined by the allowable power density of the beam. At a safe representative power density of 0.005 W per square centimeter, a receiver area of 1000 square miles is needed to process 1 trillion kilowatt-hours annually on a constant power level basis.

Tens to a few hundreds of billions of kilowatt-hours annually are more representative for regional power consumption. In that case, receiver antenna areas of the order of hundreds of square miles are needed. These are not impractical requirements, even in densely populated areas such as Europe or Japan.

Maximum Dwell Time

The most obvious, but not the only appropriate, location for terrestrial space power plants is the equatorial geosynchronous orbit (22 300-mi altitude). Because in such orbit an object is in a stationary position relative to the area over which it is located, one power plant is needed to serve a given region (e.g., North America or Africa). But there are also suitable elliptic orbits, for instance, polar elliptic orbits with their most distant point (apogee) over the North Pole (Fig. 4). This assures maximum dwell time of the power plants over the northern hemisphere, where the majority of the power consumers are located (and probably will be even 50 years hence), and where the know-how is amply available to operate and maintain the huge receiver installations. Position over the northern hemisphere allows simultaneous coverage of all longitudes down to a certain latitude depending upon altitude; whereas, in geosynchronous orbit all important latitudes are covered, but only over a limited range of longitudes. Because of the circumglobal coverage of the northern hemisphere in polar elliptic orbits, the period of revolution in the orbit matters little. The polar route, therefore, also offers greater flexibility in the international availability of spare power plants should the operation be a joint project by nations of the northern hemisphere. North America, Europe, the Soviet Union, Japan, and other nations are covered, simultaneously, as the power plant passes through the farflung arc above the North Pole, able to direct its beam where needed. Coverage of the northern hemisphere down to 40 deg latitude encompasses most of the U.S. (the southern strip and Mexico could be supplied by a high-voltage grid), practically all of Europe, the Soviet Union, northern China and northern Japan. If an orbit with a period of 12 hours is chosen, for example, four stations could provide continuous, overlapping coverage of the northern hemisphere down to 40 deg latitude. The stations can be established and maintained more cost-effectively than in geosynchronous orbit. To reach the same countries from a geosynchronous orbit, with some overlapping, the same number of stations is required. It is not important at this point to make a case for the superiority of the one or the other orbit. Of importance is the fact that several alternatives are available.

Manufacturing in Space

Space manufacturing has two basic aspects: (1) utilization of unique extraterrestrial environmental properties (such as different gravity levels and vacuum); (2) reduction of terrestrial environmental burdens from the surface, by applying the principle of division of labor between earth and the extraterrestrial domain. Just as earth is not a unique place for generating power (other than by fossil fuels), so is it not a unique place for manufacturing (other than for products relying on the processing of large amounts of rock or fossil or other organic materials).

Space environmental utilization is of interest in metallurgical processes, glass processes, crystal growth processes, and biological manufacturing processes. In the metallurgical field, unique alloys and metal products with superior properties (weight, strength, purity, etc.) can be produced. Glasses with superior optical characteristics and base materials for advanced semiconductors can be produced in the low-gravity environment of space. Single crystals of larger size, higher purity and higher crystallographic perfection for electronic, optical, and other applications can be manufactured in space more than on earth. Finally, biological materials (serums, viruses) of highest purity can be produced in weightlessness. Initially, the biological and crystal growth manufacturing groups offer the greatest promise, because they combine significant product improvement over terrestrial manufacturing with acceptable transportation demands.

The second aspect — the reduction of terrestrial environmental burdens from the surface of the earth — can have a far more incisive effect on our world and on the future of man's resource base. It involves both the environmental effects of the manufacturing process proper, and the environmental effect of extracting the mineral resources.

In principle, all industrial activity could be transplanted into space, that is, into near-earth orbit. The worthwhileness of it depends on the objective. The objective must meet a vital need to justify the effort.

If reduction of the terrestrial thermal burden is the objective, then the move would defeat its purpose if the raw materials must be supplied from earth. The reason is simply that delivering a ton of material into orbit releases more energy into the biosphere than is released in processing either the raw material (primary processing) or in working it into manufactured goods (secondary processing). Using Saturn V as an example, virtually the entire energy content of the first stage, namely 5.6 million kilowatt-hours, is injected into the biospheric portion of the atmosphere — 41 000 kW-h per ton of payload delivered into low orbit. Presently, it takes 17 000 kW-h to gain the 1 ton of aluminum from 2 tons of alumina. In the future, this value is likely to decrease to about 15 000 kW-h. In generating 15 000 kW-h of electricity, 30 000 to 37 000 thermal kilowatt-hours are released into the environment. In transporting 2 tons of alumina (plus consumable carbon for the electrodes used in the electrolytic process of extracting the aluminum), approximately 90 000 kW-h would be released into the biosphere by a Saturn V type transport to produce 1 ton of aluminum.

Of course, Saturn V would not be a suitable transport. Conditions could be improved by the use of more advanced nonchemical transports. The ultimate would be a gas-core, reactor-powered, air-breathing transport, capable of reaching orbital velocity by air-heating at only negligible fuel consumption for final maneuvering in space. Such a vehicle would release about 3500 thermal kilowatt-hours per ton payload into the atmospheric biosphere, or about 8000 kW-h per ton of aluminum produced in orbit. But even this would provide a significantly favorable thermal balance only for aluminum, since the next highest consumer (electric furnace ferroalloys) requires less than 6000 kW-h per ton.

Besides the thermal burden, chemical pollution is, in principle, a possible reason why it might be desirable to remove an industry from earth into space. But at least in the metal manufacturing industry, as distinguished from the primary metal industry (mining, metallurgy), pollution by itself is not likely to become a sufficient justification. The principal chemical burdens in the manufacturing industry are generated by industries which depend to the greatest part on organic raw materials that are uniquely earth's.

Compared to the secondary (manufacturing) metal industry, the primary sector (mining, refining) is a far worse chemical polluter. It would, then, be more worthwhile to remove the primary sector.

If delivery of metals from extraterrestrial sources is considered, orbital manufacturing assumes a different complexion. Raw materials are delivered at no terrestrial thermal burden. Little thermal burden is involved in delivering products from space to earth, even if the atmosphere is used as energy absorber. The bulk of the energy is dissipated as heat in the outer and upper atmosphere (above 100 000 ft), which is outside the biosphere. Thus, metals and metal products can be delivered from the extraterrestrial domain for indefinite time periods with virtually no detrimental environmental effects, certainly incomparably smaller effects than if they were produced on earth.

Minerals and Our Planet

Except, perhaps, for a very distant speculative future, the only way to obtain the needed metals in needed quantities is through the processing of minerals. It is, therefore, not possible to think in concrete terms of a condition in our technological civilization where we will no longer be dependent on minerals.

Mining produces the largest amount, so far, of inorganic waste: upwards of 1 billion tons annually in the U.S. alone, exceeded only by the 1.3 billion tons of organic agricultural waste (manure and refuse). Compared with the wastes from mines, the amount of wastes and sewage from manufacturing plants, homes and office buildings (350 million tons in the U.S.) appears almost small. Acids from metal processing are among the most biocidal polluters.

But the ultimate problem is the finite amount of reserves available in the earth's crust. Only a relatively very small amount of reserves of each metal is found in ores in sufficient concentration to be mined economically with present methods. This is especially true of many important nonferrous metals.

Can terrestrial reserves support an at least 40- to 160-fold increase in the next 100 years; and, more importantly still, can they sustain this consumption level for a long period of time? Based on presently known reserves, the answer is clearly negative for a number of important nonferrous metals, such as lead, zinc, silver, mercury, bismuth and probably also copper, tin and cobalt. There is always the possibility that new ore reserves will be discovered, especially in conjunction with earth resources surveys from space. There are also certain possibilities in recycling, but they can at best only slow down unavoidable dissipation and, moreover, are of no help in satisfying demand increases. Also, there is the possibility of mining ever poorer grades down to common rock.

What about the oceans? Most mineral and chemical resources will, in the next 50 years, be those that can be gained from seawater and from the relatively shallow continental shelves. But these are the biologically most important and most sensitive regions of the oceans. Extracting metals from the ocean bottom at depths of 1000 ft or more requires the development of an abyssal technology, an accomplishment that is no easier or less costly than developing the space technology required for extraterrestrial mineral resource utilization. Even aside from development problems, the vacuum technology of space cannot help but lighten the terrestrial burden and the threat to life's roots in the oceans, while ocean-bed mining cannot help but do the opposite, since it appears unavoidable that effluents and tailings are pumped directly into the sea.

Land mining at increasing depths faces a formidable problem of locating promising ore in the first place. Exploiting reserves located at great depths requires also the development of a new, abyssal technology. Exploiting progressively lower-grade ore and, perhaps, eventually rocks will, like ocean floor mining and land mining at great depth, steadily increase production costs. In addition, mining lower grades demands the processing of growing amounts of material, causing rapidly spreading land devastation, and pollution. Mining by nuclear detonation — the only way in which the exploitation of ore below certain grade levels, or of rocks, could be made economically viable — appears to be out of the question in view of the environmental implications except, perhaps, in combination with the exploitation of reserves on land at great depths beyond the danger of radioactive gas escaping to the surface or radioactive substances poisoning ground water (Fig. 5).

But even if the full potential of science and technology is brought to bear, the mineral resource limitations of one single planet simply cannot sustain continued exploitation at much higher than present levels on a long-term (even centuries long-term) basis, because environmental constraints do not permit exploitation of even the limited reserves. Thus, "placing all our eggs" into the terrestrial basket adds up to a losing proposition.

Minerals are the one natural resource that is widespread in the inner solar system and the asteroid belt. It is also a fact that the earth is more sensitive and, in this sense, a less suitable world for massive mineral exploitation than any other body in the inner solar system — as the furniture of the living room is a less suitable source of wood for the living room's fireplace than supplies in the woodshed or garage.

Earth is not merely a spaceship. It is a member of the Sun's convoy traversing the vast ocean of our Milky Way galaxy. We are separated from our sister ships by greater distances than our land surface is from the bottom of our oceans. But far more important than distance is the nature of the intervening medium.

It is very fortuitous that we need only to traverse open space to reach our extraterrestrial resources, rather than ocean depths or miles of earth's crust to reach our remote terrestrial mineral resources. It is equally fortuitous that our companion worlds are not other earths. One intelligent species is probably as much as most solar systems can accommodate. Our companion worlds are underdeveloped. Earth is the only luxury passenger liner in a convoy of freighters loaded with resources. These resources are for us to use, after earth has hatched us to the point where we have the intelligence and the means to gain partial independence from our planet — and where the time has come to convert our earth from an all-supplying womb into a home for the long future of the human race, finally born into the greater environment of many worlds.

On those worlds we can bring nuclear power to bear to exploit minerals with an efficiency that would be prohibitive on earth. This changes the basis for exploitation inasmuch as lower grades can be exploited more efficiently than on earth. We have the nuclear muscle to break an asteroid apart, or to work the crust of another planet extensively, in order to get at needed minerals.

Some will see in this a threat to soil other worlds as well as our own. But like every creature, we cannot help soiling something by living. One of the most thoughtless statements, parroted ad nauseam ever since rational concern for our environment exploded into an emotional syndrome, calls man the only animal that soils its own nest. Every animal soils its nest with the products of its metabolism if unable to move away. Space technology gives us, for the first time, the freedom to leave our nest, at least for certain functions, in order not to soil it.

Mineral exploitation is not the cleanest business in the world. But soiling an asteroid or a desolate place on another planet cannot reasonably be equated to continued soiling of the earth. Moreover, pollution assumes an entirely different, and far less critical, meaning in the context of the extraterrestrial environment. This environment is an inorganic world, exposed to a steady stream of biocidal, ultraviolet radiation and particle flares from our sun, both of which would constitute pollutants par excellence if they could flood our terrestrial environment. There is nothing that man's exploits on other worlds could add to make things worse in the vast expanse of the solar system.

Extraterrestrial mining of mineral deposits will be made possible by using nuclear explosives (Fig. 5), or possibly by nuclear fusion torches investigated more recently by Atomic Energy Commission (AEC) researchers, to break rocks and ore bodies — an extraterrestrial version of Plowshare. Absence of a significant atmosphere in most cases, and low gravitational pull, will permit easier escape of radioactive materials, thereby reducing the fallout on the worlds in question.

Metallurgical methods will have to be revised for absence of water and for use of gases of different composition than are used on earth. However, oxygen is fairly abundant in chemical (e.g., silicon) compounds from which it can be extracted. Oxygen is an important ingredient in some beneficiation methods — the first step in nonferrous metallurgy, where waste is removed, concentrating the valuable mineral into smaller bulk for subsequent steps in refining. The large energy requirements for electric smelting, high-frequency induction melting, electrometallurgy, and perhaps modified forms of pyrometallurgy can easily be provided anywhere by nuclear-electric or nuclear-thermal power plants.

Transportation Costs

For the transportation from the moon or the planets to be economically viable, the energy must be very inexpensive and metal transporters must travel in relatively slow paths. To be inexpensive, the energy must be extremely concentrated and the materials (expellant) expended in propelling the transporters must be small in mass and low in cost; or they must be provided at the place of mining. With the exception of the latter possibility, which is uncertain, only nuclear fusion meets these conditions. Because of the large payloads, the transporter requires high thrust values. Fusion drives, operating through pulsed energy release, can most readily attain high thrust values while keeping propellant consumption low. Their operation uses a sequence of detonations somewhat analogous to the operation of a combustion engine. In the latter, a piston is propelled by chemical detonation. In the pulsed fusion drive, an elastic device absorbs the energy shock from the detonating nuclear pulse, thereby driving the spacecraft forward.

The energy-releasing device is a nuclear fusion charge of adequate strength. The energy transmitting device is an expellant which could be either a metal or hydrogen (or water), depending on design specifics of the engine.

Figure 6 surveys the propellant cost of an interorbital transport having a dry weight of 1000 tons (2.2 million pounds), capable of delivering a useful payload of 3000 tons (6.6 million pounds) from an extraterrestrial resource base to earth. In order to determine the propellant cost, the following assumptions were made:

1. The cost of the nuclear fuel is $ 424 000 per kiloton (10^{-14} $/erg).

2. The cost of the expellant is negligible compared to the cost of the nuclear fuel or the cost of transporting the expellant from earth to orbit.

3. The earth-to-orbit transportation cost of nuclear fuel and expellant is $ 20 000 per ton (about $ 10 per pound, or 10 times less than with presently projected shuttle, assuming a much larger earth-to-orbit shuttle some 30 years hence).

4. The transport carries as payload on its outbound flight the fuel and expellant needed for the return flight where its payload is 3000 tons of extracted metal.

The result is shown for three levels of transportation energy, corresponding to: (1) 10 km/sec; (2) 20 km/sec; (3) 40 km/sec each way. Lunar missions are well under the level of curve (1). Mars missions would fall near to, or somewhat above curve (1). Asteroid missions would lie between (1) and (2), Mercury missions between (2) and (3). Each curve shows the propellant cost per kilogram payload versus the nuclear energy expended on the round trip at the defined level of transportation energy.

The minima shown in Figure 6 are representative. They indicate cost figures that are economically viable, especially for the 10 km/sec and the 20 km/sec level, if compared to the cost of some metals already today.

Of course, the figures in Figure 6 are far from being the total cost — even the total transportation cost. The latter includes the cost of ship maintenance, loading and unloading, and crew maintenance during layover times in earth orbit and at the target. These additional transportation costs can presently be detailed only on a highly speculative basis. But they will hardly as much as double the indicated minima. Possible reductions in nuclear fuel cost or reductions in earth-to-orbit transportation cost would have a far greater effect.

The point to be made here is that contrary to a generally held presupposition, interorbital transportation costs can be decreased to a competitive level. Transportation costs need not be the principal constraint, 50 yr hence.

It is interesting to note that in order to bring home 3000 tons of metal from the lunar surface, a nuclear energy of only about 50 kt need be expended for the round trip; and only some 150 to 200 kt to return 3000 tons from the Mars complex or from asteroids.

Many consider this way out or look at it with derision or skepticism as to its practicality, while at the same time we are compelled by our primordial instincts to pile up vast megatonnages to keep each other in line.

Future of Man

The central concept is the preservation of man and his future. This means the preservation of both the natural terrestrial environment and the infinite world of man, because he needs both. They were one in the past. But this one-world era is drawing to a close. In the future, they will encompass many worlds and, thereby, the world of man may become one — a world so savagely divided in the past.

But for this to happen, man's root planet must be his seat of power, not his cage — his root complex with the crown reaching to the stars. In this and in the next century, man will experience a transformation without equal since he emerged on this planet. He must have new options to cope with his altogether new existential universe.

Earth and space are indivisible. Together they represent the greater environment of tomorrow through which the balance between man and planet can be restored, so that both his terrestrial birth environment as well as the needed boundlessness of his world can be maintained for the long future.

In the greater earth-space environment a practical division of labor can be developed in which maximum advantage is taken of each of the three principal environmental regimes: earth, space, and other worlds in the inner solar system. Earth resource management from space, power generation in space for consumption on earth, and minerals from other worlds in the inner solar system — these are only the beginnings recognizable to us today of an evolution in which the nonuniqueness of earth becomes one of the important keys to the long-range future of the human race.

While we must correct the mistakes of the past, it must not be done by discriminating against the future — and that is precisely what we are doing if we do not work concurrently toward broadening our option base, especially in the greater earth-space environment. Because we are emancipated from the natural environment on a massive scale, we must invest more heavily than ever in the future of a human race that must rely primarily on its genius, not on its terrestrial environment, to provide for its future needs, physical and emotional. For we alone are responsible from now on for ourselves, our planet and our solar system to the end of our time.

Orbits are the new lands of our time. Before we even get to settle on another celestial body, we can build growing installations in space whose architecture rests as safely on the dynamic foundations of celestial mechanics as our terrestrial architecture rests on the static foundations of the ground. Earth and space must be interconnected by safe and cost-effective routine transportation.

Large space cities will eventually no longer only occupy earth satellite orbits, but circle our sun at different points in earth's orbit. Space cities, with giant factories and food-producing facilities, will maintain their own merchant fleet of spacecraft, their own raw material mining centers on other celestial bodies, and be politically independent city-states, trading with earth, forming new cultural cells of mankind whose choice of living in space has increased tremendously and adding to the plurality of human civilization.

Perhaps, as we place the extraterrestrial domain into the service of all people, we may be permitted to hope for the greatest benefit of all: that the ugly, the bigoted, the hateful, the cheapness of opportunism, and all else that is small, narrow, contemptible and repulsive becomes more apparent and far less tolerable from the vantage point of the stars than it ever was from the perspective of the mudhole.

After all, should we not take a cue from the fact that since the beginning man has placed his dreams and aspirations among the stars and his nightmares into caves whence he came?

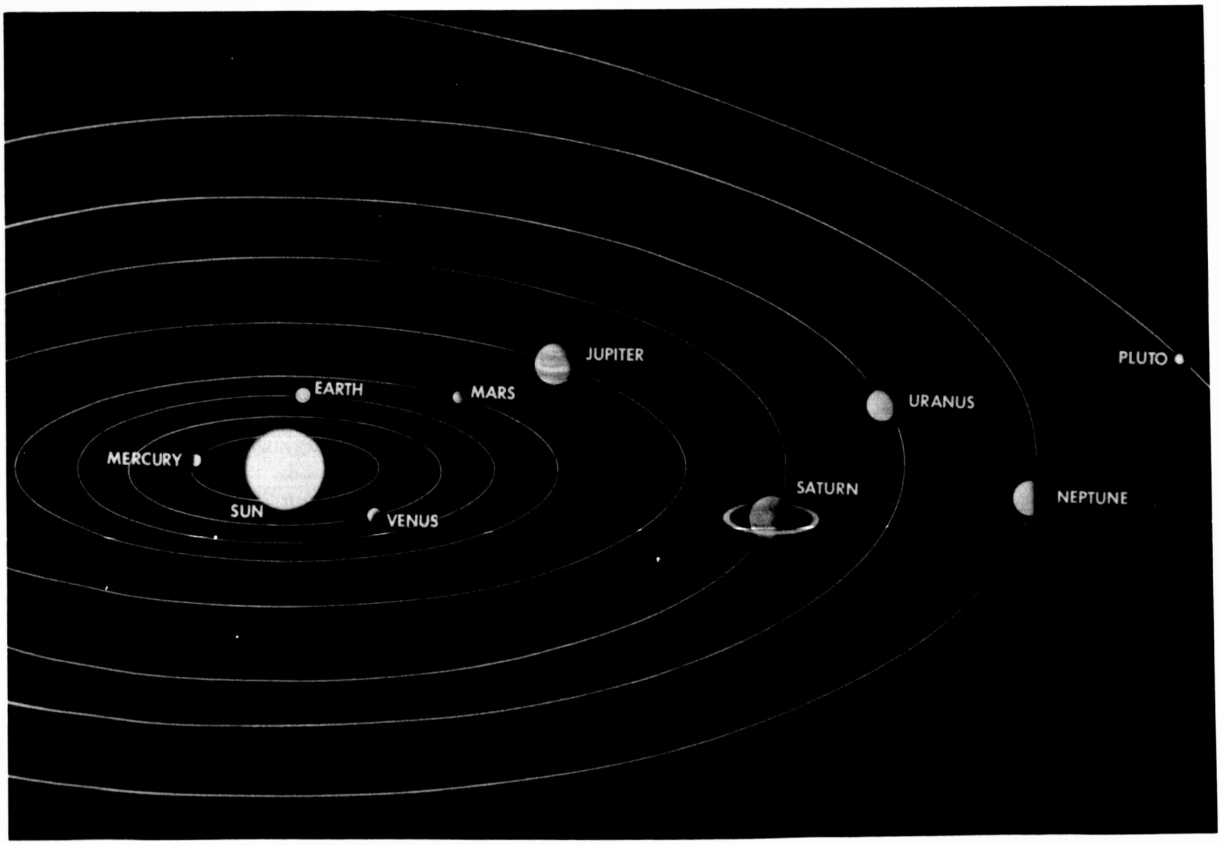

Figure 1. The solar system.

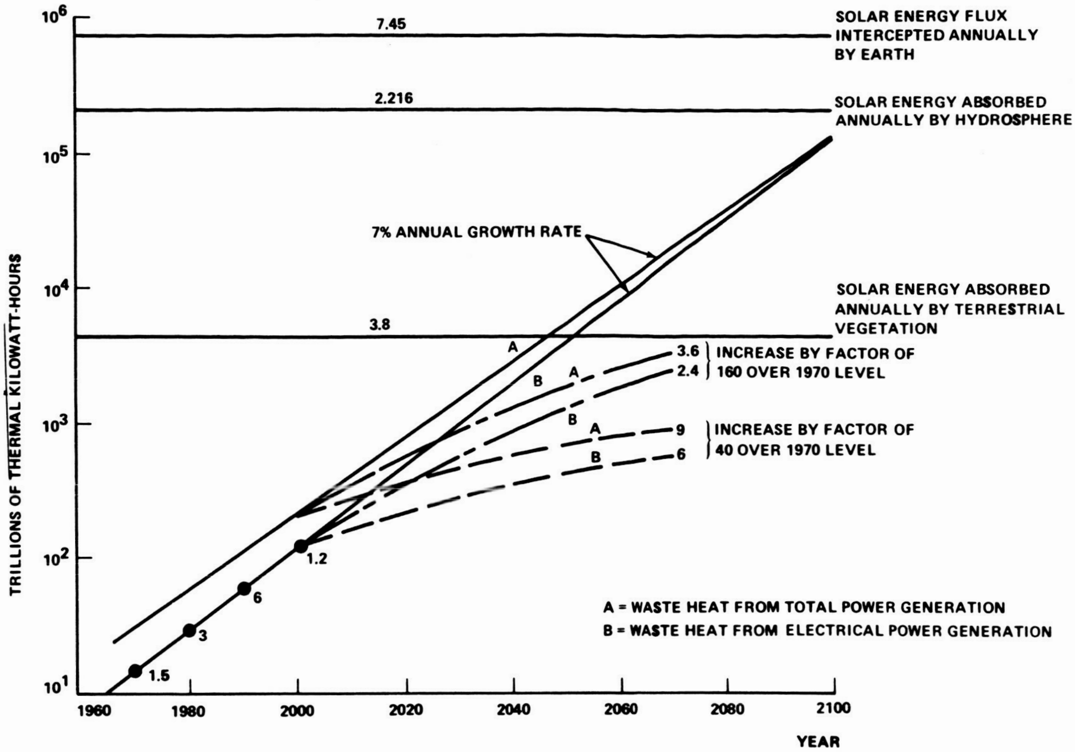

Figure 2. The thermal burden.

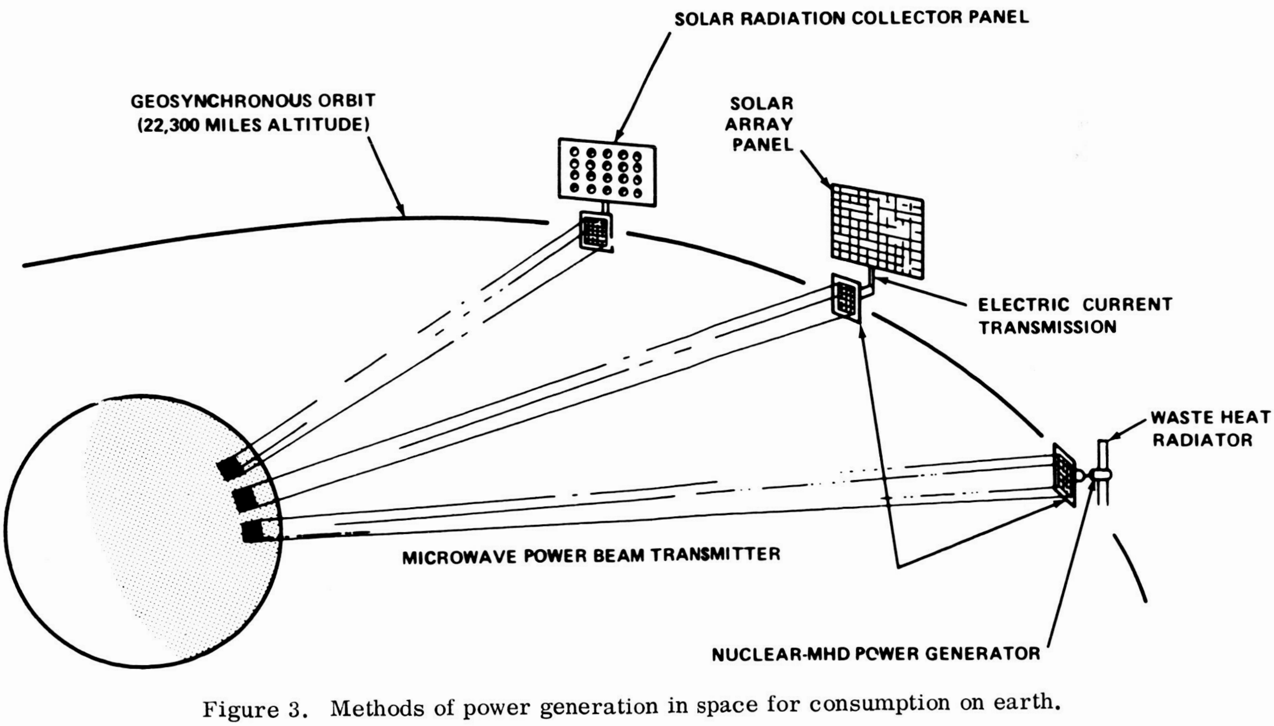

Figure 3. Methods of power generation in space for consumption on earth.

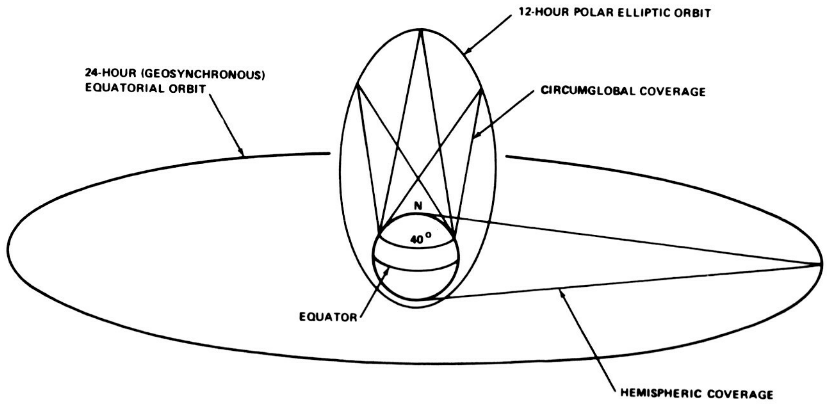

Figure 4. Choice of power station orbits.

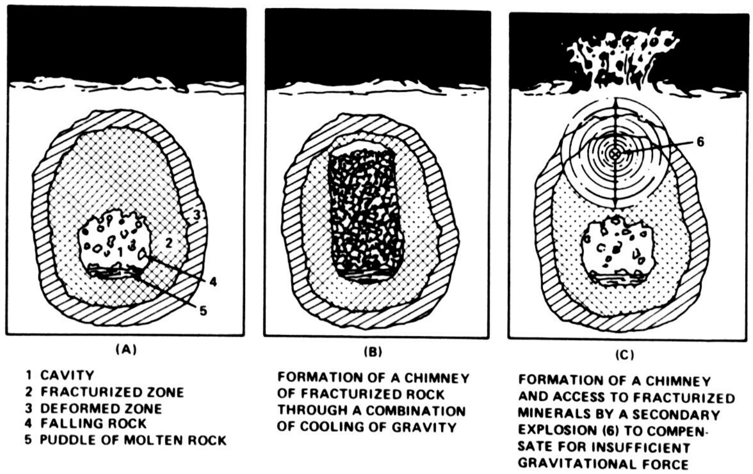

Figure 5. Extraterrestrial mining.

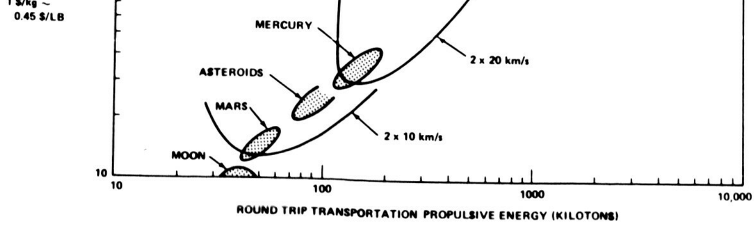

Figure 6. Interorbital transportation propellant cost for 3000-ton payload nuclear pulse freighter for specific destination.